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THE PROBABILITY FOR MISCLASSIFICATION IN THE
WERTHEIMER-LEEPER WIRING CONFIGURATION CODE

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An examination is made of the probability for misclassification in the Wertheimer-Leeper wiring configuration code (WL-code), which has been used in health studies as a surrogate for magnetic field exposure. The average misclassification rate over all exposure levels is calculated to be 39%, implying only a 61% probability that a subject is classified correctly under the WL-code. Similar results are found for exposure dichotomies under the code. Differentiation is less ambiguous between the end-pole and very-high-current-configuration classes; however, the misclassification rate here is still 29%. These results are consistent with the WL-code representing a poor surrogate for magnetic field exposure.

1. Introduction

Several epidemiological studies (Wertheimer and Leeper 1979, 1982; Savitz et al 1988) have reported a weak association between homes classified as being near high current electrical wiring configurations and the incidence of cancer. The wiring configuration codes used to classify homes were based simply on the homes' proximity to various visible components of the electrical distribution system, such as transmission lines and transformers. These wiring configuration codes could also be correlated with measurements of power-frequency magnetic fields inside the home. This observation has supported speculation that the wiring code may actually be a surrogate for residential magnetic field exposure. Since then there has been an explosion of research interest in examining the possible association between magnetic fields and cancer. The issue has attracted the attention of the public and the press, because of the prevalence of electricity, and thus magnetic fields, in everyday life.

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In fact, the correlation between the standard Wertheimer-Leeper (WL) wiring configuration code (Wertheimer and Leeper 1982) and measurements of the time-averaged magnetic fields is very weak; one of the most widely-accepted studies (Kaune et al 1987) has reported it to be 0.41. Furthermore, the large data spread when plotting residential fields against appropriate WL-codes suggests the possibility for errors due to misclassification. This can occur either by classifying a home as exposed when it is actually unexposed, or by classifying a home as unexposed when it is actually exposed. The effect of any misclassification will be to bias risk estimates when extrapolating from a WL-code/cancer association to a magnetic field/cancer association.

In this work we evaluate the extent of misclassification of study subjects resulting from the use of the WL-code as a surrogate for magnetic field exposure. Our results show a high probability for misclassification between all levels of the code, and contradict the assumption that the WL-code represents a good surrogate for magnetic field exposure. This may indicate that the reported association between the WL-code and cancer are due to an exposure agent other than magnetic fields: traffic density (Savitz and Feingold 1989), for example, or corrosion in water distribution pipes (Kavet 1990, 1991).

2. Misclassification: Concepts and Theory

A subject in a risk study, in the final stage of analysis, will be assigned a *classified exposure status* depending on the classification protocol; the subject could be ranked using a multilevel exposure metric, for example, or could simply be classed as either exposed or unexposed. The subject would also have a *true exposure status*. A correct classification would mean that the classified and true exposure status for the subject would be the same; if they were not, the subject would be considered to be misclassified (Flegal et al 1986, Copeland et al 1977).

The question of misclassification is also one of *differentiation*; if subjects in class A and B can be differentiated well, there will be a low probability of misclassification, *M*, between the two classes. In this section we examine the quantitative characterization of misclassification, through the use of the 2x2 *differentiation table*, from which we can define the *sensitivity* and *specificity* of a classification protocol such as the WL-code.

2a. The 2x2 Differentiation Table

The distribution of study subjects according to true exposure status and classified exposure status can be summarized in a 2x2 table, which we call a *differentiation table* (not to be confused with a 2x2 risk-analysis table), as follows:

Table 1.

The 2x2 differentiation table for analyzing the probability for misclassification in a given classification protocol.

		True Status	
		E	nE
Classified Status	E	A Number of truly exposed subjects correctly classified as exposed	B Number of truly unexposed subjects incorrectly classified as exposed
	nE	C Number of truly exposed subjects incorrectly classified as unexposed	D Number of truly unexposed subjects correctly classified as unexposed

In the above table, *E* represents exposed status and *nE* represents unexposed status.

We may then characterize the rate of misclassification in a given exposure protocol by specifying two important quantities, defined as follows:

- The *sensitivity* (S_e) of a certain protocol is the probability that a truly exposed subject is correctly classified as exposed. The quantity $(1 - S_e)$ gives the probability that a truly exposed subject is incorrectly classified as unexposed (misclassified).
- The *specificity* (S_p) of a certain protocol is the probability that a truly unexposed subject is correctly classified as unexposed. The quantity $(1 - S_p)$ gives the probability that a truly unexposed subject is incorrectly classified as exposed (misclassified).

Using the quantities in the differentiation table above, the sensitivity and specificity of a given protocol are given, respectively, by

$$S_s = \frac{A}{A + C}$$

$$S_p = \frac{D}{B + D}$$

From these two quantities, we now define the average misclassification rate M to be

$$M = 1 - \left(\frac{S_s + S_p}{2} \right)$$

This is the probability that either (a) a truly exposed subject is misclassified as unexposed, or (b) a truly unexposed subject is misclassified as exposed.

2b. Protocol Characterization: A Numerical Example

It will be helpful to look at an example to illustrate the use of the equations above. Consider four subjects S1, S2, S3 and S4, in a risk analysis study which contrasts the occurrence of a disease between individuals who may have one of two kinds of exposures E1 and E2. Let us assume that the true exposure status for each individual is given by:

Exposure E1. Subjects S1 and S2.

Exposure E2. Subjects S3 and S4.

Consider three different classification protocols, A, B, C, and D, which will attempt to match a classified exposure status for each individual to his true exposure status as defined above. Upon the application of each protocol, let us assume that each individual is given a classified exposure status as follows:

PROTOCOL A: *Exposure E1.* Subjects S1 and S2.

Exposure E2. Subjects S3 and S4.

PROTOCOL B: *Exposure E1.* Subjects S1, S2 and S3.

Exposure E2. Subject S4.

PROTOCOL C: *Exposure E1.* Subjects S1 and S3.
 Exposure E2. Subjects S2 and S4.

To quantify these in terms of the sensitivity, specificity and the probability of misclassification for each protocol, we first construct their associated differentiation tables, as shown in Table 2 below.

Table 2.

Differentiation tables for study subjects classified under three different protocols, as in the text.

		True Status	
		E1	E2
Classified Status	E1	2	0
	E2	0	2

		True Status	
		E1	E2
Classified Status	E1	2	1
	E2	0	1

		True Status	
		E1	E2
Classified Status	E1	1	1
	E2	1	1

Table 3, below, summarizes the sensitivity, specificity and average rate of misclassification for each protocol, using the appropriate differentiation table from Table 2.

Table 3.

Sensitivities, specificities, and average rates of misclassification for four different protocols as defined in the text, using Tables (2a) to (2d).

Protocol	Sensitivity	Specificity	Average Rate of Misclassification
A (E1 vs E2)	1	1	0
B (E1 vs E2)	1	0.5	0.25
C (E1 vs E2)	0.5	0.5	0.5

The perfect protocol, A, has a misclassification rate of 0. A sensitivity of 100% means that it consistently classifies E1 subjects as E1; a specificity of 100% means it consistently classifies non-E1 (E2) subjects as non-E1 (E2). On the other hand, while both Protocols B and C have an equal chance of correctly classifying non-E1 (E2) subjects, Protocol C is less able to classify E1 subjects correctly. An assessment of these two protocols would, therefore, favor B; this is reflected in the relatively low probability for misclassification under this protocol.

It is important to note that a value of $M = 0.5$ (as in Protocol C in the example above) implies that the probability for misclassification is equal to the probability for correct classifying the subject. Classification using such a protocol would be done equally well by chance alone¹.

This sets an upper limit of 0.5, therefore, on acceptable misclassification rates. In fact, a misclassification rate greater than 0.25 could be considered to indicate a relatively poor protocol in terms of the differentiability of its classification levels. A misclassification rate much lower than 0.25 would indicate a more acceptable protocol. Equations (1) to (3), along with this arbitrary benchmark of $M < 0.25$ for adequate differentiability, form the basis for our analysis of misclassification in the Wertheimer-Leeper wiring configuration code (WL-code).

¹It is possible to obtain misclassification rates > 0.5 . However, it can be shown that protocols exhibiting $(0.5 < M < 1)$ can be inverse-transformed into equivalent protocols with $(0.5 > M > 0)$.

3. The Wertheimer-Leeper Wiring Configuration Code

Delivery systems for electric power typically consist of several stages. In the first stage after generation, high-tension wires carrying current at voltages up to several hundred kilovolts deliver power to distribution substations. At these substations the voltage is stepped down to tens of kilovolts, carried in medium-voltage primary lines; these lines carry currents which are proportionately higher than in the first stage. The primary lines extend from the substation to local transformers throughout a neighborhood, where the voltage is stepped down for the final time (to 240 V in North America). The current is then carried along secondary lines to service drops, which bring the power to individual houses. The location of these homes with respect to the various components of the distribution system mentioned above form the basis for wiring configuration code classification.

The wiring configuration classification system most used in the EMF field is the Wertheimer-Leeper code (Wertheimer and Leeper 1979, 1982), and is based on three major assumptions (Barnes et al 1989): first, that thick wires carry large currents; second, that residential magnetic fields are primarily due to the currents in these wires and that the fields fall off with distance from the power poles; and third, that the distribution system is stable over a period of time.

The WL-code first breaks down the types of wiring into 5 classes (Wertheimer and Leeper 1982):

- Class 1.* (a) Multiple (six or more) or thick three-phase primary lines.
 (b) Transmission lines.
- Class 2.* Thin three-phase primary lines.
- Class 3.* First-span secondary lines.
- Class 4.* (a) Second-span secondary lines.
 (b) Short first-span secondary lines.
- Class 5.* End-pole situations.

Residences under study are then given a current classification based on their proximity to various arrangements of the above wiring classes:

Very-High-Current Configurations

- (a) Closer than 50 feet to Class 1 wires.
- (b) Closer than 25 feet to Class 2 wires.

Ordinary High-Current Configurations

- (a) Within 50-129 feet of Class 1 wires.
- (b) Within 25-64 feet of Class 2 wires.
- (c) Closer than 50 feet to Class 3 wires.

Ordinary Low-Current Configurations

- (a) Within 130-150 feet of Class 1 wires.
- (b) Within 65-150 feet of Class 2 wires.
- (c) Within 51-150 feet of Class 3 wires.
- (d) Closer than 150 feet to Class 4 wires.

End-pole Configurations

All Class 5 situations.

Note that in the WL-code no mention is made of magnetic fields, except in its assumption that higher magnetic fields are associated with higher-current configurations.

5. Misclassification Rates for the WL-code

We are now in a position to calculate the probability for misclassification in the WL-code. First, we assign numerical values for each class in the WL-code, as follows:

WL-1. End-pole configurations.

WL-2. Ordinary low-current configurations (OLCC).

WL-3. Ordinary high-current configurations (OHCC).

WL-4. Very-high-current configurations (VHCC).

A study residence may be characterized as belonging to one above the above classes from its proximity to various elements of the electrical distribution system; this is its *classified exposure status*, as mentioned in Section 2a.

Now consider the graph in Figure 1, which shows a typical semilogarithmic scatter plot of the time-averaged magnetic field of 37 residences against their WL-code classifications (Kaune et al 1987). Since the assumption is that the WL-code can act as a surrogate for magnetic field

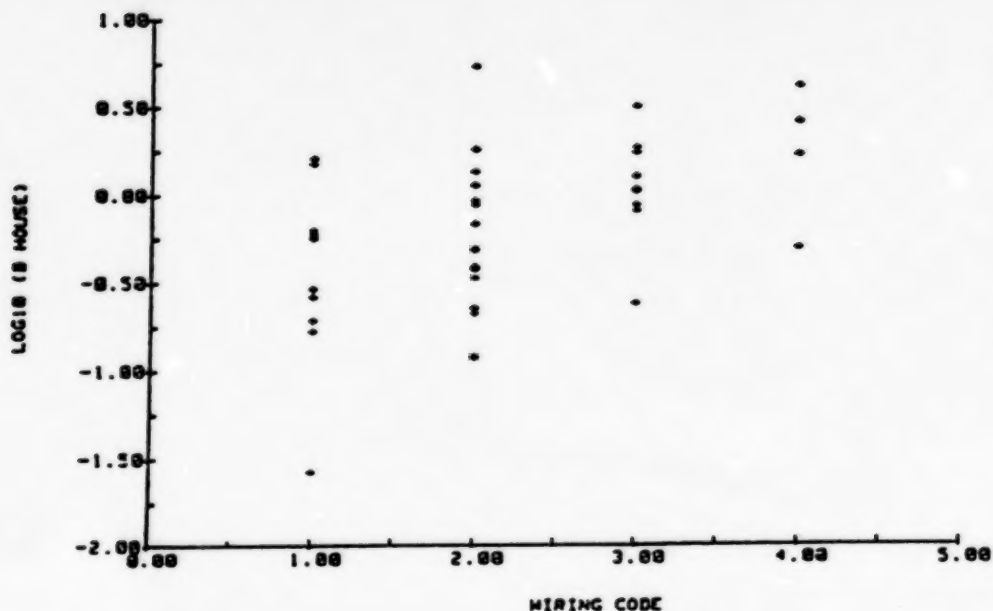


Figure 1. Scatter plot of logarithm of 24-hour-average residential magnetic flux density (in mG) and the Wertheimer-Leeper wiring code for 37 residences (after Kaune et al 1987).

measurements, the range of magnetic field intensities spanned by each WL-code class may be used to define the *true exposure status* for a particular study residence:

WL-1. Residences with 24-hour magnetic field averages from 0.02 to 1.58 mG.

WL-2. Residences with 24-hour magnetic field averages from 0.11 to 5.01 mG.

WL-3. Residences with 24-hour magnetic field averages from 0.25 to 3.16 mG.

WL-4. Residences with 24-hour magnetic field averages from 0.50 to 3.98 mG.

The correlation coefficient between the WL-code and magnetic field measurements in Figure 1 is about 0.41.

It should be noted that there is considerable overlap between the definitions for true exposure status above. The 2x2 table formalism may still be used in this situation, but with the following convention. Say we are analyzing misclassification rates between WL-1 and WL-2. Consider a residence classified as WL-1 via the wiring configuration protocol, but with a measured magnetic field of 0.2 mG. Its true exposure status may either be WL-1 (0.02-1.58 mG) or WL-2 (0.11-5.01 mG), with equal probability. In the differentiation table, this residence thus contributes a weight of 0.5 in each (true) WL-1 or WL-2 row under the (classified) WL-1 column heading. The process is then repeated for each house to complete the full {WL-1 vs WL-2} table. Using this convention, the sum of all table entries will equal the total number of residences considered, consistent with Section 2.

Table 4 summarizes the sensitivity, specificity and the average rate of misclassification between classification levels in the Wertheimer-Leeper code, using the data in Figure 1.

Table 4.

Sensitivity, specificity and average rates of misclassification between classification levels in the Wertheimer-Leeper code.

	Sensitivity	Specificity	Average Rate of Misclassification
WL-1 vs WL-2	0.48	0.64	0.44
WL-1 vs WL-3	0.68	0.63	0.34
WL-1 vs WL-4	0.88	0.54	0.29
WL-2 vs WL-3	0.67	0.47	0.43
WL-2 vs WL-4	0.84	0.36	0.40
WL-3 vs WL-4	0.77	0.38	0.42

Taking the case {WL-1 vs WL-2} as an example, the numbers in Table 4 above may be interpreted as follows:

- There is a 48% probability that a subject that should be classified WL-1 is indeed classified WL-1. Conversely, there is a 52% probability that the same subject is misclassified WL-2.
- There is a 64% probability that a subject that should be classified WL-2 is indeed classified WL-2. Conversely, there is a 36% probability that the same subject is misclassified WL-1.
- Overall, there is an average probability of misclassification of 44% between WL-1 and WL-2. The average probability that a subject is classified correctly is 56%.

If we further assume that the exposure strength is such that $\{WL-1 < WL-2 < WL-3 < WL-4\}$, the possible exposure dichotomies, and their corresponding misclassification parameters, are given by Table 5.

Table 5.

Sensitivity, specificity and average rates of misclassification for various exposure dichotomies of the Wertheimer-Leeper code.

	Sensitivity	Specificity	Average Rate of Misclassification
WL-1 vs WL-2, WL-3, WL-4	0.35	0.79	0.43
WL-1, WL-2 vs WL-3, WL-4	0.70	0.43	0.44
WL-1, WL-2, WL-3 vs WL-4	0.92	0.17	0.46

The misclassification rates for these dichotomies are similar to the ones found between individual levels in Table 4.

6. Discussion

In Section 2, it was noted that a misclassification rate of 50% ($M = 0.5$) for a given protocol implied that classifying a subject under that protocol could be done equally well by chance alone. A level of $M < 0.25$ was suggested to indicate adequate differentiability between levels in the classification protocol. Even under the best conditions ($M = 0.29$ for {WL-1 vs WL-4}), the Wertheimer-Leeper code fails to achieve this benchmark.

Furthermore, the following general observations may be made:

- Differentiation between individual levels in the Wertheimer-Leeper code is extremely poor, with average misclassification rates ranging up to 44%.
- The average misclassification rate over all exposure levels is 39%. This implies only a 61% probability that a subject is classified correctly under the WL-code.
- The best differentiation is between the WL-1 and WL-4 levels. However, even here the probability for misclassification is almost 30%.
- When dichotomizing exposure levels based on the WL-code, it does not matter where the "cut-off" high-exposure level is chosen. For any cut-off choice, differentiation between exposed and unexposed subjects is poor, with an average rate of misclassification of about 45%.

It must be stressed that the *true exposure status* of each subject used in the calculations above is based on the actual range of magnetic field intensities associated with each WL level, obtained from the data of Kaune et al (1987); the *classified exposure status* of each subject is based on classification via the number and location of elements of the electrical distribution system, also from the same work. The large misclassification rates, and thus the poor differentiability between WL-code levels, are a direct consequence of the definition of true exposure.

It is possible that the definition of exposure in terms of the time-averaged strength of the magnetic field (the magnetic flux density) is erroneous, and that other field characteristics, such as harmonics or transients, may be the important metric. However, numerous field exposure metrics have been previously examined, among them spot measurements, 24-hour-average measurements, single-component measurements and root-mean-square measurements. All these metrics have failed to show as strong a correlation with health effects as has the WL-code (Armstrong et al 1990, Barnes et al 1989, Kaune et al 1987, Savitz et al 1988).

Recent studies have reproduced the association of the WL-code with adverse health effects. Exactly what the WL-code does measure is still to be established. However, the most plausible explanation for the results in this work is that the Wertheimer-Leeper codes are not a surrogate for magnetic field exposure, but instead indicate an alternative exposure agent, such as traffic density or corrosion products in water pipes (Kavet 1990, 1991, Savitz and Feingold 1989). Further work should be explored in order to ascertain the effects of these and other possible alternative agents, as well as to estimate the effect of confounding, on risk analysis studies involving health effects, magnetic fields and wiring configuration codes.

7. Conclusions

We have calculated the probability of misclassification when using the Wertheimer-Leeper wiring configuration code as a surrogate for magnetic field exposure. As an average over all exposure levels, the misclassification rate is calculated to be 39%, which implies only a 61% probability that a subject is classified correctly. We found similar results when analyzing exposure dichotomies under the same protocol. Differentiation between the end-pole and very-high-current-configuration (VHCC) classes is less ambiguous, but still poor, with a probability of misclassification of 29%.

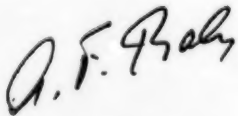
Considering that a misclassification rate of 50% is equivalent to classifying by chance alone, these results contradict the assumption that the WL-code represents a good surrogate for magnetic field exposure. This may indicate that the possibility of association between the WL-code and cancer due to an exposure agent other than magnetic fields, such as traffic density or corrosion in water distribution pipes, cannot be ruled out.

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